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NEXT GENERATION INFORMATION SYSTEMS ARCHITECTURES

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14. ABSTRACT
This effort concerns a new aerial ad-hoc networking paradigm, in which low-altitude unmanned aerial vehicles (UAVs) are used to assist wireless communication among a set of stationary or mobile ground stations. This work focuses on the use of cost-effective Commercial Off-The-Shelf (COTS) equipment. New networking protocols have been developed based on antenna engineering and interference-resilient medium access control (MAC) schemes. In addition, the project has gathered a substantial amount of measurement data from actual field experiments to support future design activities such as throughput-optimizing flight-path design.

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Executive Summary

Work of this project has led to a number of findings and conclusions. Most of these results have been published:

- "Field Experimentation of COTS-based UAV Networking," IEEE MILCOM 2006, October 2006
- "Wireless Local Area Networks: Why Integration Is Inevitable," in The Broadband Explosion: Leading Thinkers on the Promise of a Truly Interactive World, R. D. Austin and S. P. Bradley (Editors), Harvard Business School Press, 2005
- "Design of an OFDM Cooperative Space-Time Diversity System," IEEE Transactions on Vechicular Technology, Vol. 56, No. 4, July 2007, pp. 2203-2215
- "Construction of Block Orthogonal Golay Sequences and Application to Channel Estimation of MIMO-OFDM Systems," Vol. 56, No. 1, January 2008, pp. 27-31
- "AANET: Aerial Ad-hoc Networking," Harvard Ph.D. Thesis by Chen-Mou Cheng, May 2007

Reprint of the two publications are attached to this report.

In the rest of this document, we focus on a main contribution of this project concerning a novel aerial ad-hoc networking architecture (see the attached first publication). In this paradigm, low-altitude unmanned aerial vehicles (UAVs) with wireless communication capability are used to assist networking among a set of ground stations. This new paradigm is attractive because UAVs can be dynamically deployed in a wide variety of geographical territories. Furthermore, UAVs often have high-quality, line-of-sight communication links with other UAVs and ground stations as aerial links usually suffer relatively little shadowing compared with their terrestrial counterparts. We emphasize the use of commercial, off-the-shelf (COTS) components because of their high performance and economical cost, thanks to the positive cycle between market demand and technology advancement.

In this work we have demonstrated that the new paradigm can help solve performance problems due to interference in multi-radio, multi-hop networks. Although solutions such as antenna engineering and interference-robust medium access control can effectively mitigate multi-radio interference, multi-hop interference stands unsolved despite numerous attempts by the wireless research community. Using UAVs to ferry data can alleviate such interference by avoiding excessive multi-hop forwarding.

Field experimentation is indispensable to the understanding of the working of these new UAV networking systems comprising COTS components. For this reason, we have waged a

measurement campaign using a UAV networking testbed. We have developed a set of efficient tools for trace collection and data visualization. We demonstrate the efficacy and advantages of our methodology with a number of sample experiment results. We have developed visualization tools to reveal certain interesting interactions of the testbed with the environment that are otherwise hard to identify. Moreover, we have characterized the aerial link quality under various circumstances. Such link quality may fluctuate rapidly due to changes in UAVs' positions, velocities, as well as attitudes. Using regression and non-parametric statistical analysis, we compare and quantify the prediction capabilities of several existing models that take into accounts factors including distance, antenna gain pattern, antenna cross polarization, and, in some cases, ground reflection. We summarize the findings in a few compact guidelines for the designers of future aerial ad-hoc networking systems. We hope that our effort provides a useful foundation upon which new airborne applications and networking protocols can be developed.

Summary of Results

1. We study the fundamental reasons that prevent the performance of a wireless ad-hoc network from scaling up for high-throughput applications over a wide geographical area of interest. We identify the culprit to be the multi-radio and multi-hop interference. We propose an assortment of solutions to combat interference and validate the efficacy of these solutions via field experimentation. We conclude with a novel viewpoint: the withstanding problem due to multi-hop interference will simply vanish if we introduce into the solution space an extra dimension of physical mobility of data-ferrying UAVs.

2. We inquire into the new UAV networking paradigm through an extensive set of experimentation and measurement with a prototype system that we build using COTS components. With this new prototype system, we collect a substantial set of data on general link quality in UAV networks. Furthermore, we present visualization of the collected data for the purpose of exploratory analysis. It helps identify large-scale trends and correlations in environmental factors and performance. It also helps us gain new insights into the system behavior in various settings.

3. Using regression and non-parametric statistical analysis, we quantify the portion of variance in link quality that can be explained by various factors and conditions. Based on this quantification, we compare and distinguish the most accurate statistical model for predicting link quality among a number of existing models in the literature. Knowing when and which model is more accurate is important, for it provides a foundation upon which the development of new applications and optimization techniques can be based.

FIELD EXPERIMENTATION OF COTS-BASED UAV NETWORKING

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ABSTRACT

Low-cost and high-performance Commercial Off-The-Shelf (COTS) wireless equipment, such as IEEE 802.11 wireless LAN ("Wi-Fi"), has so advanced that it is now practical to use it in small low-altitude Unmanned Aerial Vehicles (UAVs). This new capability has inspired many novel application ideas in UAV networking. We argue that field experimentation of UAV networking is essential in collecting link measurement data, developing network protocols and applications, and evaluating their performance in realistic environments, and that it is feasible to conduct these experiments cost-effectively with COTS-based equipment. We describe several ongoing field experiments and initial results. Lastly, we briefly describe future testing plans as well as suggest methods of facilitating rapid and inexpensive UAV networking field experimentation.

INTRODUCTION

Potential applications of COTS-based UAV networking for low-cost small UAVs are abundant. For example, UAVs could act as relays between ground objects that could not otherwise communicate due to distance or lack of line-of-the-sight; multiple UAVs could simultaneously record and track the count of wildfires; and UAV networking could create an instant communication infrastructure following a disaster or during sporting events. But uncertainties with these networks are also abundant. Beyond usual quality of service concerns about wireless mobile networks, there are UAV and COTS specific issues such as dynamically changing link quality due to UAV's movement and banking, and relatively low tolerance [5] of low-cost COTS wireless receivers to radio interferences.

At present, the best practices of COTS-based UAV networking and their expected performance in various airborne applications are not well-understood. Literature in this area is scarce. This is partly due to the relative newness of low-cost COTS-based radio and networking apparatuses (e.g., 802.11 equipment) and partly due to the fact that past work on small UAVs mainly focused in other areas such as UAV control (e.g., [1]) and single-plane UAV applications (e.g., [8]). As a result, it is unclear, for example, how well 802.11 COTS equipment, which was originally designed to provide local wireless access to the Internet for laptops and desktops, would work in UAV networking

In this paper we argue that field experiments are essential in improving our knowledge in COTS-based UAV networking. This is because real-world UAV networking and the environments in which it expects to operate are far too complex to be addressed by other means (e.g., simulation or modeling alone). For instance, it would be necessary to carry out field experiments in collecting link measurement data, developing network protocols and applications, discovering networking system issues (e.g., tradeoff between throughput and latency) and validating solutions. Furthermore, we argue that by using COTS communications equipment and UAV platforms, relatively quick and inexpensive field experiments are feasible. We suggest methods that can facilitate such rapid and low-cost field experimentation of UAV networking. For illustration, we describe some ongoing field experiments that we are conducting.

DESIGNING FIELD EXPERIMENTS FOR UAV NETWORKING

There are a number of issues regarding the design of field experiments for UAV networking. As discussed below, these include considerations concerning link measurement, communications and networking protocols, test payload, and applications.

Design of Link Measurement Experiments

In developing UAV networking applications and protocols, it is important that we can characterize UAV wireless links under various environments of interest. For example, we need to know link performance

against metrics such as Receive Signal Strength Indication (RSSI), UDP throughput and packet loss rates.

The communications environment where a UAV network operates is usually much too complex to be captured by simple models, such as free-space propagation models. Wireless links of a UAV may exhibit varying quality over time due to a variety of factors, including changes in communication distance, antenna polarization caused by airplane's banking, direction of the communicating party in the antenna radiation pattern, shadowing resulting from blocking of line-of-sight by on-board electronic equipment, ground reflection and Doppler effects. Furthermore, when a UAV communicates with nodes on the ground, multi-paths caused by reflections from ground as well as nearby objects, such as trees, hills, buildings and vehicles, can affect the quality of the communication channel. These objects may sometimes block line-of-sight. In addition, there could be radio interferences from other ground transmitters in the region operating at the same or adjacent frequency bands. This interference problem can be especially serious for 802.11 equipment, given its widespread deployment.

For these reasons, it is necessary to conduct UAV field experiments to collect measurement data that can accurately characterize a UAV's wireless communication links in environments of interest. The design of such experiments will involve the design of the UAV fly (e.g., altitude, speed and flight pattern), position and elevation of ground nodes, type and orientation of antennas on the UAV and ground nodes, traffic load (e.g., selection of traffic source and destination nodes, uni- or bi-directional transmission, transmit rate and packet size), etc.

Design of Protocol Experiments

Consider, for example, a multi-hop UAV network, where packets are relayed by one or more UAVs. Such a multi-hop relaying network can extend network range and provide communication beyond line of sight.

There is a large design space for multihop protocols, ranging from the traditional single-radio, single-channel protocol based on CSMA/AD to multi-radio multi-channel protocols based on CSMA/CD, TDM or FDM [5]. At the physical layer, we need to ensure sufficiently high Signal to Interference plus Noise Ratio (SINR) for each hop, in the presence of possible radio interference from the neighboring hops [9] and adjacent channel interference (ACI) from the same node [4][10]. At the MAC layer, in selecting a proper wireless link to use a node may send probe packets to test link quality. At the network layer, unlike conventional hierarchical routing for the wired Internet, routing for ad-hoc UAV networks likely needs to be flat. That is, all nodes are on the same level and perform routing functions. For example, every node must maintain or discover routes to the destination [7].

In a UAV network which experiences rapid change of link conditions, the chance that all links on a multi-hop path are in good conditions at the same time is likely to be small. Future experiments will characterize the probability and characteristics of this multi-hop environment. In this case, it would be useful for a relay UAV to buffer outgoing packets when its outgoing link experiences poor link conditions. This buffering method would be similar to the Delay Tolerant Networks (DTN) approach [3].

For these reasons, we need to design UAV networking experiments to explore protocol design space, and evaluate new approach such as DTN-like protocols.

Design of UAV Test Payload

While these aforementioned issues concerning communication links and networking protocols could be complex, solutions must nevertheless be simple, lightweight and flexible. Specifically, they need to satisfy physical constraints imposed by a small UAV, with respect to form factor, weight, battery budget, etc.

For example, a small UAV based on a 96" wingspan Senior Telemaster (see Figure 2 and 3) can afford only a networking payload of low single digit pounds, while carrying fuel or batteries sufficient for a half to one hour flight. In addition, there is space constraint that only allows a processor board of size not larger than 5"x8". Within the space constraint, accessories such as bulk data storage, radio cards, and batteries also need to be accommodated. Some applications would require the inclusion of other payload components such as GPS and camera.

Beyond satisfying physical constraints of a small UAV, the payload design typically needs to meet some additional objectives. For example, the design

may need to be flexible to allow frequent component changes, friendly in payload access to facilitate field operation, and ruggedized to endure aircraft's shaking and temperature variations.

An integrated part of the networking payload is the placement of radio antennas and their cables. These antennas are for radio control (R/C) of the airplane and for its data communications (e.g., 802.11 radios). The R/C antennas would need to be placed sufficiently far from the on-board processor board to reduce interferences. In one of our early payload designs, we observed serious interference on a 72MHz R/C receiver by a 100MHz processor board on the UAV. We later used a multi-prong approach to mitigate the interference problem: (1) moving the R/C equipment including receiver and antenna, to the tail of the airplane, (2) shielding the box hosting the processor board with metal screen wrap, and (3) replacing an external power switch of the processor board with an internal switch to minimize radio frequency interference. For data communications we have been using custom-made dipole antennas that can be conveniently mounted at desired locations of the UAV wings.

Design of Application Experiments

Through application-level experiments, we can evaluate the overall end-to-end application performance of a UAV networking system. Application experiments could be, for example, a UAV's retrieving of sensing data from sensor nodes on the ground, a UAV's relaying of packets for ground networks, and UAV-to-UAV multi-hop packet or message relaying. It is useful to focus on essential mechanisms shared by multiple applications. For example, for UAV packet relaying and data retrieving applications, we could design experiments to evaluate relay and retrieving mechanisms, respectively.

A key to the success of these application mechanisms is their ability of adapting to a UAV's dynamically varying link quality. For example, it would be desirable that the encoding of video taken by a UAV can dynamically adapt to the condition of the UAV's output link. That is, the encoder will produce a high-rate video stream when the link is good and a low-rate one otherwise.

FIELD EXPERIMENT CASES

We describe two of our ongoing COTS-based field experiments in UAV networking. The first experiment uses 802.11 equipment, whereas the second one uses 900MHz technology. The two experiments complement each other in the sense the former and the latter address high-bandwidth and long-range communications and networking needs, respectively. Future experiments will integrate both systems and use them simultaneously.

Case 1: UAV Networking with COTS 2.4GHz and 5GHz 802.11

We have conducted field experiments for UAV networks based on 2.4GHz and 5.8GHz COTS 802.11 equipment for the past nine months. The experimentation has progressed through a number of stages. Experiments were first performed in labs, then in some large indoor spaces (e.g., a gym) and open outdoor grounds, and finally, in an airfield. Network nodes were first placed on the ground, then on antenna towers and balloons, and finally, on UAVs. Through these stages of experiments, we calibrated our network equipment, refined system software, improved the design of our UAV networking payload, wrote various scripts for running experiments, and developed data analysis and visualization tools.

Figure 1 is a flight path plot of a UAV run in a set of experiments conducted in April 2006. The purpose of the experiment was to measure link quality for communication between a UAV and ground nodes, under various communicating distances and antenna configurations. The UAV used was a gas-powered model airplane (Senior Telemaster). In the diagram per-second UAV positions, obtained by a GPS receiver mounted on the UAV, are shown as dots on the UAV flight path. The UAV flew approximately at 50-yard altitude and at 40 miles per hour speed over four ground network nodes. Three of the ground nodes had their antennas placed about 12" above the ground, whereas the fourth one was mounted on the top of a 14-ft wooden pole.

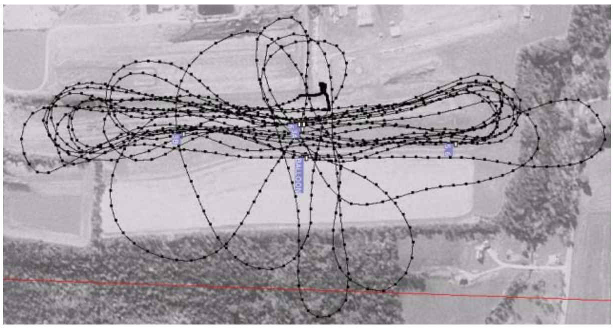

Figure 1. UAV flight path recorded by an on-board GPS receiver

In one of these experiments, the UAV was equipped with two radios each with two antennas. These four antennas were mounted on the UAV wings (see Figure 2) in the three orientations: (1) "vertical to the ground", (2) "horizontal to the ground and parallel to the flight direction" and (3) "horizontal to the ground and perpendicular to the flight direction". Using these antennas one at a time in a round-robin manner, the UAV broadcast data packets to the four ground nodes. Each ground node was equipped with two radios each with its own antenna. Both radios of a ground node simultaneously receive packets broadcast by the UAV. Our measurements on throughput suggest that the pair of horizontal antennas that are orthogonal to the flight path perform better than others for most of UAV positions (see [6] for a detailed accounting of the measurement results). Based on these results, we can devise strategies for dynamic and automatic selection of optimal antenna pair to use during a UAV flight.

Figure 2. Custom-made dipole antennas mounted on a UAV wing

In a recent UAV flight test, with our custom-made antenna, we were able to demonstrate greater than one mega-bit-per-second throughput in a three-hop network involving two relay UAVs.

In another experiment, we compared range reachable by 802.11a with that by 802.11g. Generally speaking, with 802.11g the UAV can communicate to ground nodes easily even when it is as high as 600ft above the ground. Thus with 802.11g robust communication between UAVs and ground nodes is feasible. In [2] similar results were reported for 802.11b. These results have led to some of our current application experiments focusing on evaluating networking performance between UAV and ground nodes. To enhance the robustness of the communication, we are investigating the use of ground node clusters as relays. That is, any node in a cluster can receive broadcast packets from a UAV and can transmit packets for the next hop. These clusters can thus increase redundancy in the relay operation so as to improve the relay reliability and throughput.

Case 2: UAV Networking with COTS 900MHz Technology

Preliminary runs of a second set of experiments has been accomplished using COTS 900MHz technology in a point to point mode. The focus of this set of experiments is the development of mechanisms and tools for the collection of data characterizing the performance of various communications link technologies. As with the previously discussed 802.11 experiments, a Senior Telemaster (see Figure 3) was used and these experiments were initially developed and prototyped in a laboratory environment.

Figure 3. Electric powered Senior Telemaster with a 900MHz serial RF modem hosted in the middle section of the fuselage

900MHz Serial Modem

As depicted by Figure 4, the payload for this set of experiments consists of a small Soekris processor

board running Linux, a COTS 900MHz serial RF modem (Microhard Systems' MHX-920), and a small GPS receiver. The processor sends test data including GPS information to a corresponding processor at a ground location. The ground node calculates and logs effective throughput, packets in error, total packets, RSSI and GPS information. This information is displayed on a ground workstation and logged for later processing. GPS information is also passed to an external application for real time display of platform position tracking.

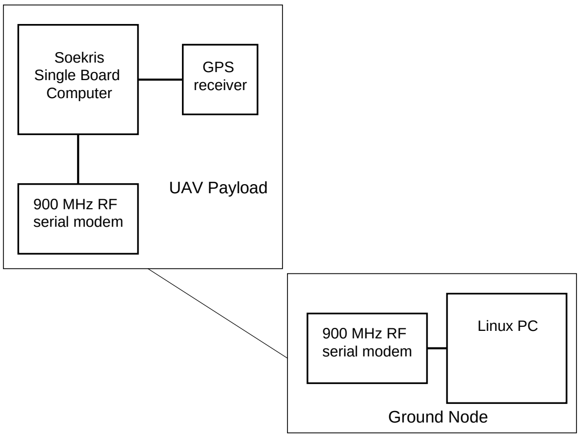

Figure 4. 900MHz serial modem test onfiguration

Minimal testing has been done to date in determining how RSSI and throughput vary as a function of communication distance. For these tests the UAV's distance from the ground receive antenna is roughly 8 miles. Altitude of the platform ranged from approximately 350 – 900 feet. More testing is needed to gather enough data to draw relevant conclusions, but the use of small COTS platforms and equipment has supported the ability to easily collect the necessary data.

900MHz 802.11

We have also tested another 900MHz approach using the recent Atheros' 900MHz wireless solution based on the 802.11 protocols. Our UAV field experimentation has found that this solution has significantly longer communication ranges than 802.11a/b/g, while still being able to achieve megabits per second bandwidth. The long range property of this technology under a 1-megabit-per-second transmitter is clearly demonstrated in Figure 5. Ranges of up to 2000 meters were attained from aircraft to ground vehicle, in a tree filled rural environment.

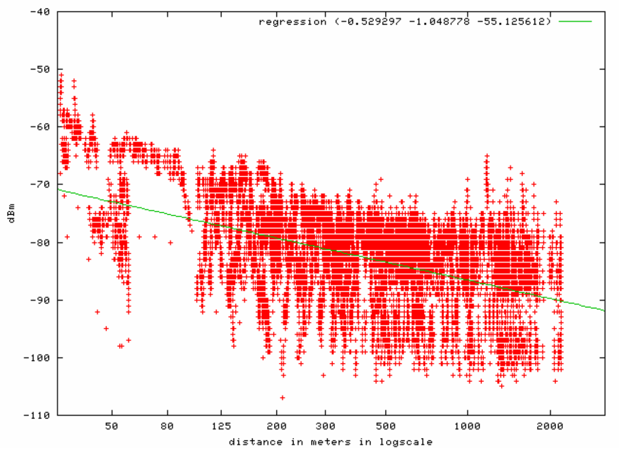

Figure 5. RSSI (in dBm) as function of distance (in meters) for 900MHz 802.11

FACILITATING RAPID FIELD EXPERIMENTS

Rapid progress in collection of measurement data depends on our capability of doing quick, inexpensive field experiments. There are multiple factors that can facilitate rapid field experiments, including flexible aircraft platform capabilities, staged and scripted experiments, flexible mobile lab to support flying and outdoor experiments, and separate teams for flying UAVs and for conducting communications and networking experiments. Below we discuss these factors.

Flexible UAV Platforms

Several capable, Almost Ready to Fly (ARF) model aircraft platforms exist which are quite capable of carrying adequate test payloads. Advances in battery and motor technology have made electric flight a clean, easy, quiet option for test flying communications and networking payloads. Several platforms have been evaluated and tested for support of rapid, flexible experimentation. Two are outlined here. The Senior Telemaster, as depicted in Figure 3, is a 96" wingspan covered balsa aircraft with a lifting stabilizer. The aircraft provides adequate fuselage space for payloads, with a structure that offer many options for payload configuration. The SIG Rascal is 110" covered balsa aircraft with a large fuselage, easily handling a variety of payloads. Both of these platforms possess stable flight characteristics, with the ability to carry several pounds of payload. Power options include gas power, glow fueled engines, or electric motors.

While small platform airborne testing can be done using conventional RC model aircraft control, the use of an autopilot greatly enhances the ability to perform effective testing. It eases the workload of test personnel, while generally providing the ability for better monitoring of aircraft parameters, effective automation of test flights, as well as better repeatability of test conditions. Some of our testing has made use of Procerus' Kestrel autopilot. The unit's ease of installation, configuration and use provides a capable system, effectively support a variety of tests, and eases pilot workload during the performance of tests.

Staged and Scripted Experiments

Even the simplest of experiments is complicated when we move from a laboratory environment to the field. As indicated earlier in our discussion on UAV networking experiments, a set of staged experiments that gradually build up the capabilities of performing experiments are useful. In order to maintain organization, and support smooth performance of test scenarios, it would be useful to make use of checklists and scripted procedures for execution of tests.

Flexible Ground Support Infrastructure

The availability of COTS aircraft platforms and wireless equipment provides relatively simple tools with which to test and analyze communications technologies. However, as with any work based on field experimentation, the amount of equipment, software and ancillary items required rapidly escalates. Note also that fly related operations are typically performed in more remote areas. A method for organization and transportation of assets is thus a key enabler of successful testing.

Among several solution options in this area, we will cover our use of a specially outfitted trailer, depicted in Figure 6, for field test support. The trailer contains support infrastructure (including battery recharging facilities), storage and workspace for the performance of a variety of communications and networking experiments.

Figure 6. A mobile test support trailer to facilitate field experiments in UAV networking

The basic trailer is a standard commercial 6x12 foot enclosed single axle trailer. Support infrastructure consists climate control, as well as power distribution. "Shore Power" connections connect to commercial AC or generators. The trailer also contains a DC power system, drawing power from deep cycle batteries to provide AC power. This capability provides electrical support for short duration testing without requiring generator operation.

Processing, networking and communications resources include PC platforms, network hubs and wireless routers, and RF equipment. These resources can be rapidly reconfigured to support various testing requirements via patch panels and interconnects. This flexibility is fundamental to the trailers ability to support testing. As the types of communications being evaluated is constantly changing, communications capabilities, including RF units and antennas are swapped in and out as needed.

A Separate Crew Responsible for Flying

In our testing performed to this point, successful testing is a direct result of adequate manpower. More specifically, when utilizing UAVs, a separate crew for operation of the airborne platform as well as its maintenance and repairing improves the execution and safety of the testing. Isolating operation of the networking and communications payload from the operation of the platform allows personnel to focus on a specific aspect of the testing, providing improved oversight and test management.

FUTURE EXPERIMENTATION

Many opportunities exist for future testing expanding on these experiments presented herein. In the area of communication link characterization, additional modems and radio solutions have been identified for comparison. Multiple antenna types will be characterized to determine their performance in typical small UAV environments. This information will be used to identify appropriate solutions for data connectivity to small UAV platforms, taking into account their characteristics and operating environments. Areas of specific interest include antenna placement, appropriate power levels, cost vs. range and dynamic antenna selection.

Testing and analysis of current wireless channel access protocols will proceed in a similar fashion to link analysis and testing. Additional work will be done in the characterization of the small UAV multi-hop environment. Future work will assess the characteristics of multi-hop architectures, measuring latencies, probability and duration for link connectivity, and end to end path characteristic in representative environments. Of special interest is the area of mobile ad-hoc and mesh network technologies, as well as emerging delay tolerant networking techniques.

CONCLUSION

Due to the availability of low-cost and yet highly capable COTS-based communications equipment and UAV platforms, it is now feasible to conduct rapid and inexpensive field experiments for UAV-based networks. These experiments can easily, and at low cost, yield test data that is more accurate and realistic than current simulation, modeling and assumptions. This accurate data is crucial to the development of novel UAV applications and networking protocols. In this paper we have described issues in designing UAV networking experiments, some ongoing field experiments, and methods of streamlining field experiments. We expect that these new experimental capabilities will significantly improve our knowledge on how to make best use of the UAV networking in the next several years.

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Wireless Local Area Networks: Why Integration Is Inevitable

H. T. Kung

It is increasingly evident that the growth of wireless local access networks (WLANs) based on 802.11x standards like Wi-Fi will soon be massive and widespread. Enterprises and end users are enthusiastically committing resources into WLAN deployment to benefit from the technology. This phenomenon resembles the widespread deployment of private wireline Ethernets in the 1990s.

The rapid deployment of WLANs in homes, offices, and public areas, and the relatively inexpensive bandwidth of WLANs are prompting many observers to ask how the emergence of WLANs will affect the telecom industry. Some see WLANs as direct competitors to the telecommunications high-bandwidth third-generation (3G) technologies; others view the two phenomena as complementary.[1] Some perceive WLANs as providing mainly mobile data services, while others expect WLANs to generate a new wave of opportunities in voice services.[2]

This chapter will examine the fundamental reasons why the impact of WLANs on telecommunications will be profound, even though it is too early to predict the specific implications for particular industrial sectors or for the definitions of standards. We will offer an analytic roadmap, with analysis and

application scenarios, of how WLANs could be integrated into telecommunications devices, systems, and services. We view this integration process as only the latest instance of the merging of existing communication and data networks, with WLAN-enabled cellular handsets as a convergence point. Such handsets can be viewed as an initial focal point in the integration of WLAN in telecoms, in the sense that they are certain to bootstrap other integration efforts.

Usage Examples of WLANs in Telecoms

We expect many users to be eager to use cellular handsets for WLAN access. The ability to access WLANs with handsets, when in a WLAN environment, would represent a welcome convenience for those who always carry cellular handsets and regularly use WLANs in their homes and offices via other devices. These users can now use some handsets to download and upload multimedia content and messages, conduct video conferencing, and play interactive cellphone games over high-bandwidth, inexpensive, always-connected WLAN connections. Today, however, they must tolerate the inconvenience of switching to a PDA, laptop, or desktop with a WLAN interface before they can access a WLAN.

Early versions of dual-mode handsets that support both cellular and WLAN connections are already undergoing market trials.[3] Other models are expected to become available shortly. Consider, for example, the various smartphone handsets currently on the market, which implement PDA-like functionality with cell-phone form factors. It will be relatively straightforward to enable these handsets to support WLANs, since many PDAs already have built-in or add-on WLAN interfaces and protocol stacks to run applications such as Web

browsing and instant messaging. Indeed, a recent exhibition demonstrated a number of WLAN applications on an existing smartphone handset by using a WLAN card inserted into the SD card slot.[4]

Another possible scenario is the use of WLANs by fixed-wire phone operators to provide local loops and to access Voice over IP (VoIP) services from data links such as DSL/cable lines, which would represent a last-mile alternative for operators and a convenience for their subscribers. These subscribers can now use WLANs to access PBX systems or phone lines with the WLAN-enabled portable phones or the dual-mode cellular phone handsets described above. In WLAN-enabled homes and offices, cellular handset users can thus leverage the convenient features of handsets (phone books, caller lists) while consuming higher-quality and possibly also cheaper noncellular phone services. Fixed-wire phone operators may very well bundle these added services with conventional DSL and cable modem offerings.

Integration of WLANs in Telecoms

From a technological perspective, integration means that cellular handsets have the dual capability of using both WLANs and telephone networks. We will call these dual-mode handsets *WLAN-enabled handsets*.

Integration also means that WLANs and cellular networks are able to interoperate at certain network layers. There are two approaches to integration, often called *tightly coupled* and *loosely coupled* internetworking.[5] In the tightly coupled approach, integration is implemented at a network layer below the IP layer. With integration of this kind, the WLAN will appear to the cellular core

network as another cellular-access network. As a result, seamless handoff between cellular and WLAN networks can be expected. Further standardization and development efforts are needed however, to realize this capability, and deployment of tightly coupled internetworking is thus likely to be years away.

The other approach, loose coupling, implements integration at the IP layer. Using IP protocols, the cellular core network can use existing authentication, authorization, and accounting (AAA) systems, such as the home-location register (HLR) or home-subscriber server (HSS), to support WLAN services and applications. That is, a terminal on a WLAN can send and receive AAA messages to and from the operator's AAA gateway over an IP network. Loose coupling is readily implementable using existing protocol standards, and it can already be useful in providing AAA and other services for WLANs. For purposes of this chapter we will assume that only loose coupling is implemented.

There are also less integrated methods, such as using a GPRS/WLAN PC card in a PC or PDA to allow it to use both GPRS and WLAN networks. Hybrid approaches of this kind can be useful in some applications, such as providing both WLAN and dial-up support for travelers. But because these solutions still require users to carry PDAs or PCs, we expect them to have less impact on telecommunications than integrated solutions.

For a more detailed discussion on integration methods, refer to the six coupling scenarios defined by 3GPP each with an increasing level of integration for the interworking[14].

The Challenges and Opportunities of Integration

Independently Developed WLANs

In loosely coupled integration, the telephone network will integrate its core with independently developed WLANs rather than using traditional access networks designed together with the core. Sometimes the core will even be integrated with WLANs which are independently deployed and managed by other operators. In this case, loosely coupled integration is a matter of integrating *private* networks (WLANs) with *public* networks (phone networks). This degree of integration of heterogeneous networks appears to be unprecedented in the telecommunications industry. Needless to say, it must be feasible not only technically but also as a business proposition.

Public WLANs

The business viability of public WLAN hotspots, such as airports, conference centers, exhibition halls, railway stations, and stores, is subject to considerable debate. These hotspots and the business opportunities they embody have attracted substantial attention from telecommunications operators, but the hotspot business has not proven as profitable as initially expected, except in places like busy airports where there are many business travelers. This pattern is understandable, given that most WLAN deployment so far is concentrated in homes and enterprises where the WLAN interface is available to users via laptops, desktops, or PDAs. Most people who visit public WLAN areas, however, are not carrying laptops or PDAs. We expect that when WLAN-enabled handsets become popular,

public WLANs and related roaming, billing, and aggregation services will see greatly increased usage.

WLANs and Voice over IP

By definition, WLANs transport IP packets, and they are thus often linked with VoIP in discussions of their use in telecoms. For some telecommunications operators, VoIP is a distraction in the sense that it diverts revenue from traditional voice services rather than increasing total revenue. The reality, however, is that VoIP-related services are rapidly gaining momentum throughout the world (e.g., the Skype VoIP services[13]), and their momentum can not be stopped. This is the case fundamentally because it makes economic sense for voice services to share packet-switching data networks, and because such sharing helps promote deployment of new data services. Telecommunications operators, ought to, at least in the long term, plan on increasing their revenue from nonvoice services, by promoting data services. WLANs' roots in the data world and existing data applications make them well suited to facilitate new data services and to create revenue in new areas such as broadband content, online games, and multimedia streaming services.

The Capacities of Handsets

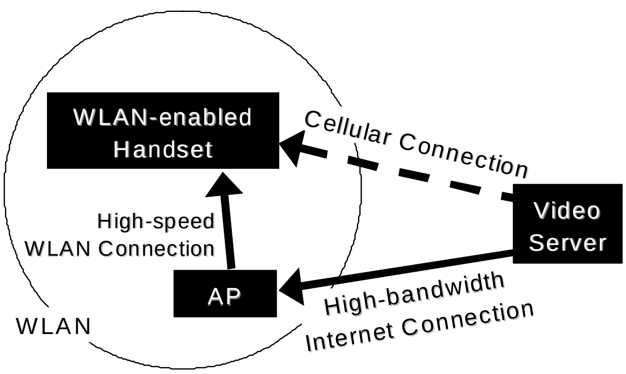
Another issue is how well WLAN-enabled handsets with stringent size constraints can make use of the high-bandwidth link offered by WLANs. In recent years, cellular handsets have substantially expanded their capabilities in computing, storage, display, and peripherals. In fact, they have become one of the most powerful and integrated multimedia devices available to consumers. For example,

with a gigabyte SD memory card, USB drive or hard drive, the storage capacity currently available in today's handsets is already large enough to accommodate an entire 90-minute movie in a compressed video format. With such prodigious storage capacity, handsets will need to use high-bandwidth and inexpensive WLANs for file downloads and uploads.

Figure 11-1 illustrates a scenario in which a handset user downloads a large video file from a remote server over WLAN. Initially, the user accesses a traditional cellular connection. Upon detecting the presence of a WLAN access point (AP), the handset reroutes the connection to the Internet to transfer packets from the server to the AP and the WLAN to transfer packets from the AP, to the handset. The new route will support data transfer at a much higher bandwidth and at a much lower cost to the user. The detection of the AP by the handset can be performed automatically using standard AP-discovery protocols. The rerouting can also be done automatically, without even breaking the connection, using techniques similar to mobile IP.[6]

FIGURE 11-1

Downloading Video via Handset over WLAN

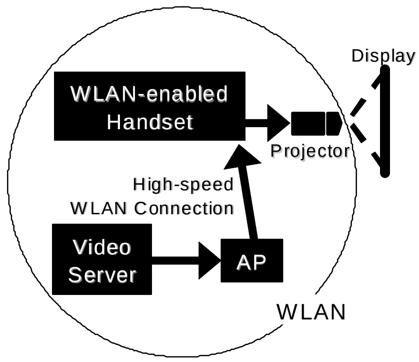


Source: H. T. Kung

A handset can receive compressed streaming video over WLAN from a video server and simultaneously send it, also over WLAN, to a projector that outputs images on a wall-mounted display, or to an LCD display, for easy viewing. (In a *Digital Home* scenario, the video server could be a so-called *home media center*, and the display could use a *home media adapter*.) Figure 11-2 depicts this video-streaming scenario. As we shall see, the handset can also decrypt an encrypted video to implement Digital Rights Management (DRM) functions on the fly. As a recent exhibition on applications of WLAN-enabled handsets demonstrated, today's high-end cellular handsets have enough computing power to perform streaming and decryption functions in real time.[7]

FIGURE 11-2

Streaming Video from Video Server to Projector via Handset over WLAN



Source: H. T. Kung

Moreover, WLANs can provide high-bandwidth, but inexpensive transport to support high-resolution Multimedia Messaging Services (MMS), videophone, and video conferencing, via handsets. Using WLANs, an MMS recipient can afford to receive "pushed" messages automatically without worrying about the

download cost or time, even when such messages are large. Like e-mail receipts, MMS recipients can enjoy the convenience of the automatic receipt of messages.

Consider, too, the use of such handsets in a video-over-IP telephone application. During a telephone session, a user can position the handset's camera to face himself, listen to the other party's voice on the handset's speaker, and watch the other party's image on the handset's display while talking to the handset's microphone. This setup is much simpler and less error-prone than an equivalent setup involving a laptop, desktop, or PDA and all the peripheral devices required for an Internet-based video phone session. With ENUM (standing for "electronic numbering" or "telephone number mapping"), which uses telephone numbers to retrieve domain names, the handset user can have the additional convenience of being able to use the same telephone number for both cellular and IP connections.[8]

As for the power consumption of WLAN-enabled handsets, the applications mentioned above are mostly indoor and stationary, and thus have easy access to power supplies. When the WLAN interface is not in use (such as during a traditional cellular call), a handset will turn it off automatically (or the user can do so) to conserve energy. Moreover, we note that when a handset uses a WLAN in a file download or upload, its WLAN interface will need only be turned on for a relatively short time, due to the WLAN's high bandwidth. Over time WLAN circuits will improve with respect to power consumption when their applications move beyond laptops and desktops to consumer electronics (such as an MP3 player or a digital camera) with stringent energy efficiency requirements.

Indeed, the development of low-power single-chip solutions for WLANs has recently been one of the most active areas in chip design.

Industry Perspectives

Manufacturers are likely to readily appreciate the value of adding WLAN support to handsets. Initially, the market for WLAN-enabled handsets, as for most new products, will be relatively small. Manufacturers of consumer products with rapid innovation cycles will take the lead in the hope of capturing the first-mover advantage—rationale that motivated some sector leaders to provide WLAN support in PDAs and other consumer electronics.

Hardware development for new WLAN-enabled handsets will leverage chips and circuits already developed for various WLAN products. Software systems, by contrast, may present a greater challenge. In particular, handset manufacturers will need solutions for WLAN protocol stacks. The smartphone vendors that use operating systems with built-in support for such protocol stacks (such as Linux, Symbian, and Windows Mobile) will have an immediate advantage.

Cellular telephone operators, on the other hand, may have trouble seeing why they ought to provide WLAN-related services before such services prove themselves viable in the marketplace. Traditionally, operators rely on cutting-edge industry-wide standards in rolling out new generations of technologies and services such as GSM, GPRS, and 3G. In this way they can share the first-mover risk by moving together. But in the case of WLAN, whose development and deployment are mostly pursued in a grassroots fashion, there is no such coherent

and unified cross-industry push. A few visionary operators may break with tradition and aggressively embrace the opportunity of WLANs on their own, but many other telephone operators will probably take a gradual approach to integrating WLAN services. Exactly how the picture will unfold is hard to discern at present. We can be certain, though, that when WLAN-enabled handsets become widely available, operators will step up the pace of integration in order to offer a vast array of new services enabled by these handsets.

A near-term initiative that many telecommunications operators can pursue is the reuse of existing authentication and billing infrastructures by applying them to WLAN services. For example, GSM cellular phones' SIM cards can be used for authentication and charging purposes for both WLAN access and content services that use WLANs for content delivery. Also, a WLAN-enabled handset user will be able to rent or purchase a video and retrieve it over a WLAN utilizing his or her subscription account with a telecommunications operator.

Alternatively, the user can pay via his or her telephone subscription account to download content covered by DRM agreement using a handset with built-in DRM support. For instance, the user may purchase a content key for a piece of MP3 music or an MPEG-4 video using his telephone subscription account, and then use his handset to decrypt otherwise unplayable content. DRM rules could be flexible: for instance, they could specify that content downloaded to the handset can only be uploaded to other devices twice and played a maximum of 10 times within the initial six months.

Cellular operators' authentication and billing systems are particularly useful for these applications, since their per-user rather than per-household setup is more suitable to mobile users who may be away from home. The system can truly support a simple-to-use "single-sign-on" mechanism that offers great convenience while providing a reasonable level of security and privacy. In addition, to the application service providers, SIM card based authentication provides a way to track customers behavior such as their buying habits on an individual basis.

ISPs have a longstanding interest in VoIP services—an interest that has recently substantially increased, in part due to VoIP's success in countries like Japan, which has millions of VoIP subscribers. Another explanation for ISPs' growing interest in VoIP is the standardization of new protocols like Session Initiation Protocol (SIP) and Electronic Numbering (ENUM), which facilitate deployment of VoIP services: the SIP protocol provides end-to-end signaling over the IP network and the ENUM system allows search by telephone number through the Domain Name Service (DNS) for such related information items as name, IP address, e-mail address, fax number, street address, personal interests, and the like.[9] A given ENUM search may not retrieve all of these items, for reasons of privacy protection (but the ability to use a telephone number to retrieve a domain name represents a significant convenience for users.) These standards enable VoIP service providers to use heterogeneous systems to provide a variety of new data and voice services.

However, VoIP still faces a formidable obstacle: the inconvenience of having to find a headset, gateway, or computer to use VoIP services. Some recently released USB and Wi-Fi VoIP handsets and embedded VoIP boxes have mitigated the problem somewhat. WLAN-enabled handsets, which support both cellular and WLAN services, will completely eliminate this obstacle.

Fixed-wire phone operators can also benefit from WLAN-enabled handsets. Subscribers often choose to make cellular calls even when a fixed-wire phone is readily available; it has been reported that in the United Kingdom about 30 percent of mobile calls are actually made from the user's home.[12] It is also commonplace to call a person at his or her cellular rather than fixed-wire number to ensure that the the person called will retrieve the caller ID from the cellular handset and pick up the call. The use of dual-mode WLAN-enabled handsets in VoIP can thus help offset fixed-wire providers' loss of subscribers and minutes to cellular providers. Furthermore, fixed-wire telephone operators will be able to provide voice services beyond the boundaries of their own local-loop facilities: they can provide VoIP services over DSL, Ethernets, or other data lines, or use WLAN as a local loop.

Cable operators also express interest in providing VoIP services. In Japan, several major VoIP service operators are backed by cable operators. Moreover, some of the cable set-top box's Digital Rights Management functions can migrate to a WLAN-enabled handset with built-in DRM support, as we saw earlier. Incorporating DRM functions in a handset is particularly natural when the handset also acts as a remote controller for a settop box.

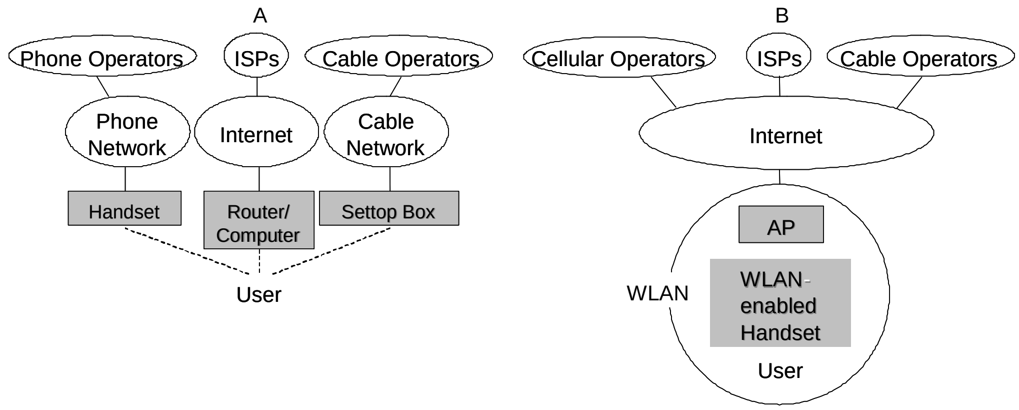
A new generation of service providers, often called "aggregators", is focusing on WLANs. Through franchise arrangements, aggregators combine the services of multiple WLAN operators under a single brand name and also provide roaming support to customers. Thus aggregators' customers no longer perceive hotspots as islands but as a large, unified wide-area network. The franchises can wield its technology and marketing power to set up new hotspots quickly, and can exercise aggregated buying power to negotiate favorable back-haul network fees. As we have mentioned, usage of hotpots will increase greatly when WLAN-enabled handsets become widely available. WLAN aggregators are likely to be major players in telecommunications services within a few years.

Three-in-One WLAN-Enabled Handsets as a Convergence Point

This picture has emerged from our discussion thus far: WLAN-enabled handsets offer the triple functions of a traditional cellular voice phone, an Internet-download-and-multimedia-communications device, and a cable set-top box's DRM capability. These 3-in-1 handsets thus represent a convergence point for three networks: a phone network, the Internet, and a cable network. Figure 11-3a illustrates the traditional setup whereby a user uses separate devices and network paths for services on the three networks. With a WLAN-enabled handset, as Figure 11-3b shows, a user will be able to reach all three networks at once over WLAN.

FIGURE 11-3A AND 3B

Alternate Network Access Models



Source: H. T. Kung

Clearly, WLAN-enabled handsets represent a keystone in WLANs' integration into telecoms. With these handsets, operators will be in a stronger position to roll out WLAN-related services.

An Agenda for the Near-Term Future

Accelerating the integration of WLANs into telecommunications providers will require further efforts in several spheres of technology, applications, and regulatory policy.

In handset technology, work in the following areas would be essential in realizing our vision about WLAN-enabled handsets and their use as outlined above:

- *WLAN-enabled handsets.* To achieve high performance these handsets should be *integrated* GSM/WLAN, GPRS/WLAN or 3G/WLAN handsets, rather than cellular handsets with plug-in WLAN modules. Furthermore,

such an integrated handset should allow simultaneous use of both WLAN and GSM/GPRS/3G at the same time.

- *Power-efficient WLAN circuits and MAC-layer protocols.* To support VoIP over WLAN, the power consumption for transmitting or receiving should be no more than 200mW, and that for simply listening should be much lower. This may be achieved with a low bit rate comparable to what is required for VoIP sessions.
- *WLAN resource discovery and control protocols.* WLAN-enabled handsets should be able to discover and control nearby resources such as projectors and data servers automatically.
- *WLAN/WLAN and WLAN/cellular handoff protocols.* These handoff protocols can support applications such as VoIP where connections will need to be maintained when a handset user moves from WLAN to cellular network or another WLAN, and vice versa.
- *Audio and video streaming.* For example, a WLAN-enabled handset can stream audio or video over WLAN to a TV or speaker via a WLAN home media adapter.
- *Latency-sensitive WLAN protocols.* For applications, which have stringent quality of service (QoS) requirements such as VoIP, we will need to minimize or eliminate delay uncertainty introduced by current protocols such as Request To Send/Clear To Send (RTS/CTS), and/or provide priority scheduling.

- *WLAN Virtual Private Networks (VPN).* Like a laptop/desktop, a WLAN-enabled handset should be able to set a VPN connection to a remote server for authentication and security purposes.
- *New peripheral interfaces such as various sensing devices.* For example, via an interface to a Radio Frequency Identification (RFID) reader, a WLAN-enabled handset can serve as an always-on mobile server that can identify RFID-tagged objects in the nearby area.

We also need to address new opportunities, such as DRM and handset controllers for various Wi-Fi appliances. Perhaps, given the popularity of Apple's iTune/iPod online music configuration, we can anticipate another successful business model based on WLAN-enabled DRM handsets. Last but not the least is the need for establishing a certification process that can certify WLAN-enabled handsets and related software.

In the application and services arena, there are multiple directions to pursue. One would address vertical markets in facility security, manufacturing, education, health care, retail, exhibition halls, tourist spots, and warehouse management, spheres in which WLAN-enabled handsets could serve the functions of communications (for instance, walkie-talkies), monitoring and tracking, and personalization in a local environment. These handsets can incorporate RFID readers to further enhance their capability to serving these markets. Such handsets would need to compete with existing solutions based on PDA devices and low-tier Digital Enhanced Cordless Communications (DECT) phone network or PHS

cellular systems. WLAN devices that do not emit strong radio interference will be necessary for environments like factories and hospitals with electronically sensitive instruments.

A new generation of WLAN-enabled operator-offered services will emerge. These might include SIM-based authentication, charging, and billing for WLAN access and WLAN-related services ("single sign-on“); MMS push, interactive cellphone games, and video telephone conferencing over WLAN; and multimedia content-download service using WLAN-enabled DRM handsets. If corresponding versions already exist on cellular phone networks or the Internet, these applications will need to be extended to WLAN environments. For example, it will be possible to port digital TV or some popular interactive online games on the Internet to WLAN-enabled handsets.

Integrating WLAN-enabled VoIP handsets in enterprises and educational institutions should be an immediate goal while fixed-wire phone companies and cable operators are developing public systems capable of using these handsets.[10] These VoIP systems can benefit from new protocols such as SIP and ENUM.

A WLAN-enabled handset will offer enormous versatility as a consumer electronics device. With its built-in speaker, microphone, camera, and recording capabilities, such a handset is a natural monitoring device for a baby’s room, a patient-care area, or a building entrance. A WLAN-enabled, handset-based monitoring system can afford an always-on network connection and can transport high-resolution pictures and videos. With its large storage capacity, a handset will function as portable storage for data and video files, similar to today’s USB

storage devices. Unlike USB storage, however, a handset can transfer files or stream video over WLAN to servers, projectors, or displays.

A WLAN-enabled handset is also a versatile control device. It can be a remote controller for any home appliance, entertainment device, or gate control with a WLAN interface. Through the attached SIM card, moreover, the handset-based remote controller can support authenticated control functions.

Regulatory initiatives will be necessary to ensure that public unlicensed spectrums for WLAN applications are sufficient and safe. For example, new regulations will be needed to discourage malicious radio interference in a WLAN environment. In the future, technology advances will allow WLANs to operate at speeds of a gigabit per second or more; thus allocation of additional unlicensed spectrum will be needed to support increased bandwidth and quality of service over WLAN.

Regulation will also need to address the management of telephone numbers. A user of a WLAN-enabled handset could use several telephone numbers on his or her handset (cellular number, VoIP number, home and work fixed-wire phone numbers, and instant messaging number). We will need to develop schemes to allocate these numbers and to encourage their convergence, perhaps through systems like ENUM.[11]

Conclusion

Integrating WLANs into telecommunication systems promises extraordinary benefits for end users. With a WLAN-enabled handset, a cellular phone user will have immediate and convenient access to a multitude of cost-effective broadband

WLAN applications and services without having to rely on a PDA or a PC. These handsets will serve as a common access device for the Internet, cable, and phone networks. The single-sign-on and always-on features of WLAN-enabled handsets are certain to inspire new application and business initiatives.

Handset manufacturers, together with ISPs and fixed-wire operators and WLAN aggregators, are expected to be among the first to mover towards integration, with WLAN-enabled handsets as an initial focal point. The initial market for WLAN-enabled handsets will probably outstrip the market for PDAs within a few years, given that these next-generation handsets will include a WLAN interface and PDA-like functionality. When such handsets become widespread, other sectors—such as public WLANs—will take off as traditional cellular operators and WLAN aggregators aggressively promote WLAN services. All telecom sectors, including cellular operators, should be prepared to offer services that incorporate WLAN capabilities.

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